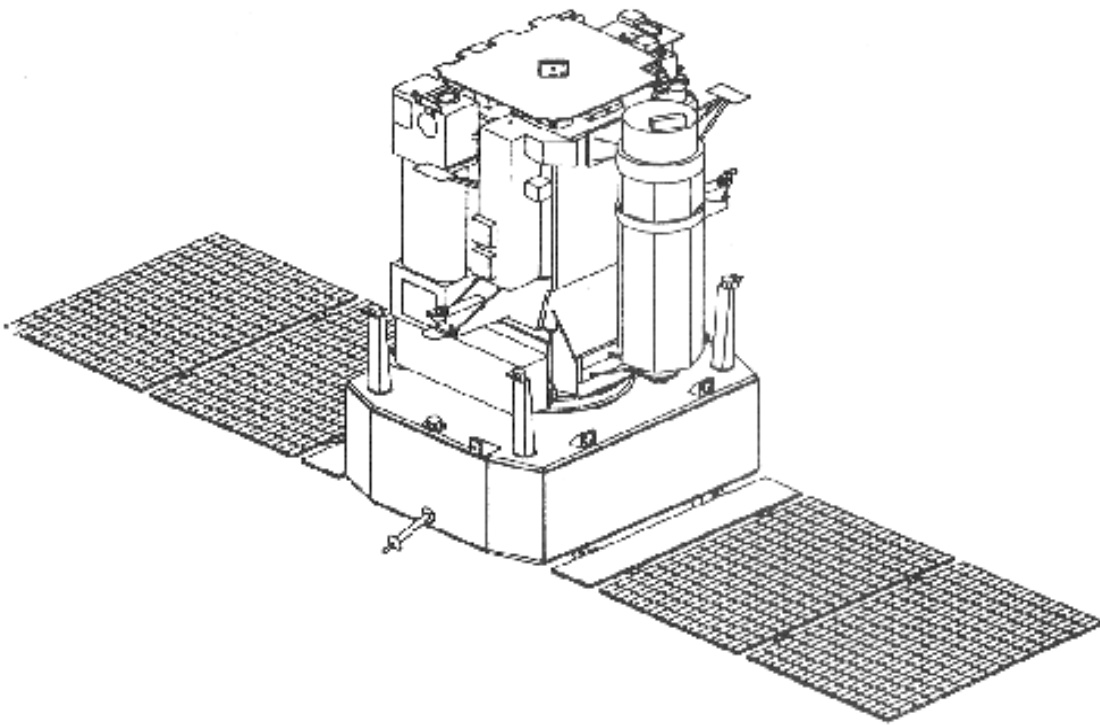


SOHO

Update on the wheel speed anomaly

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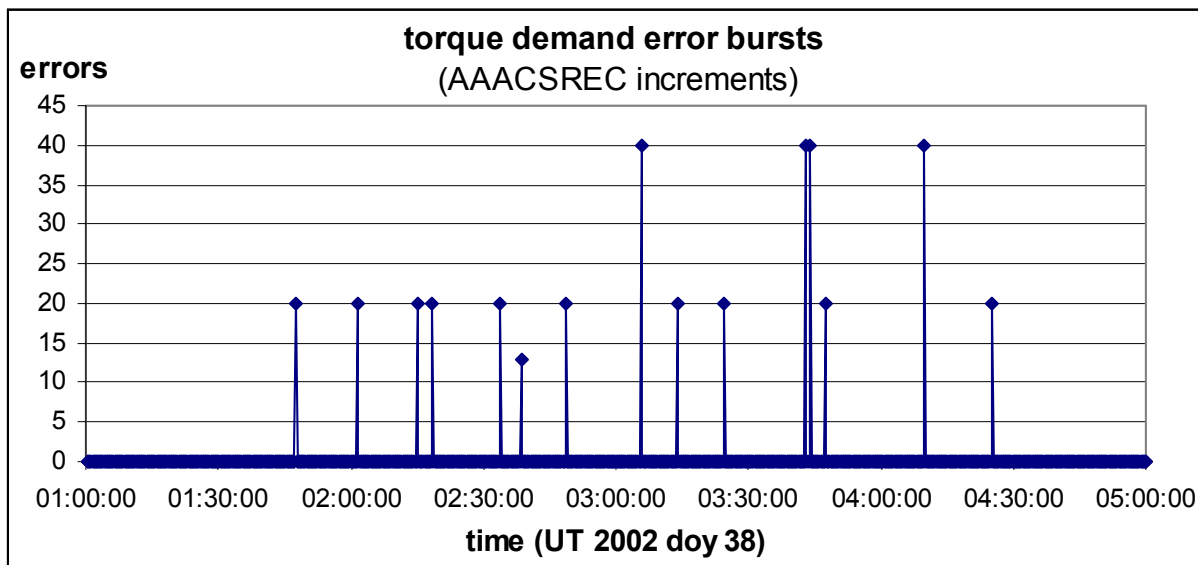
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1 Introduction

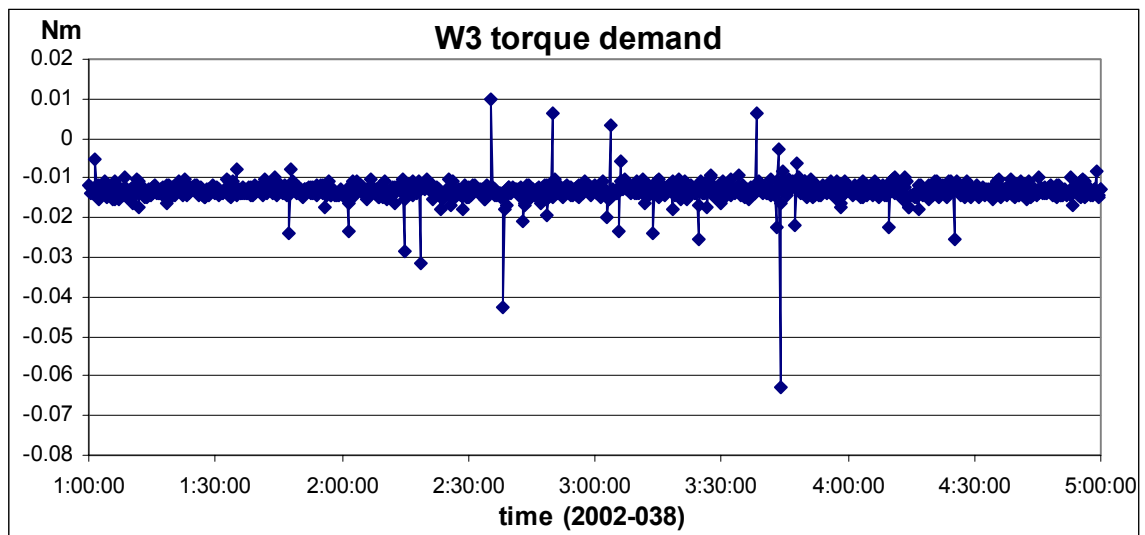
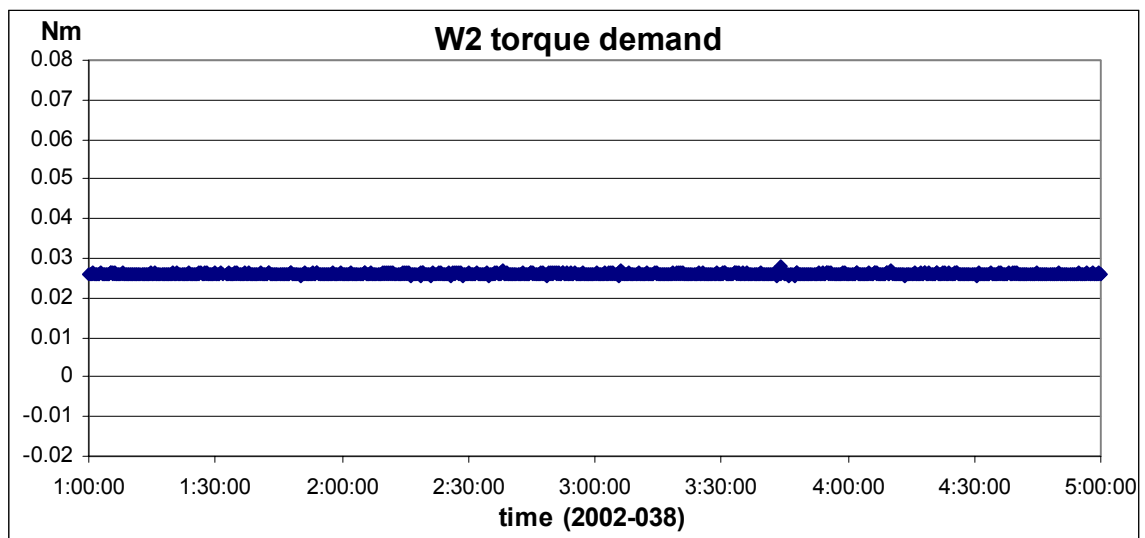
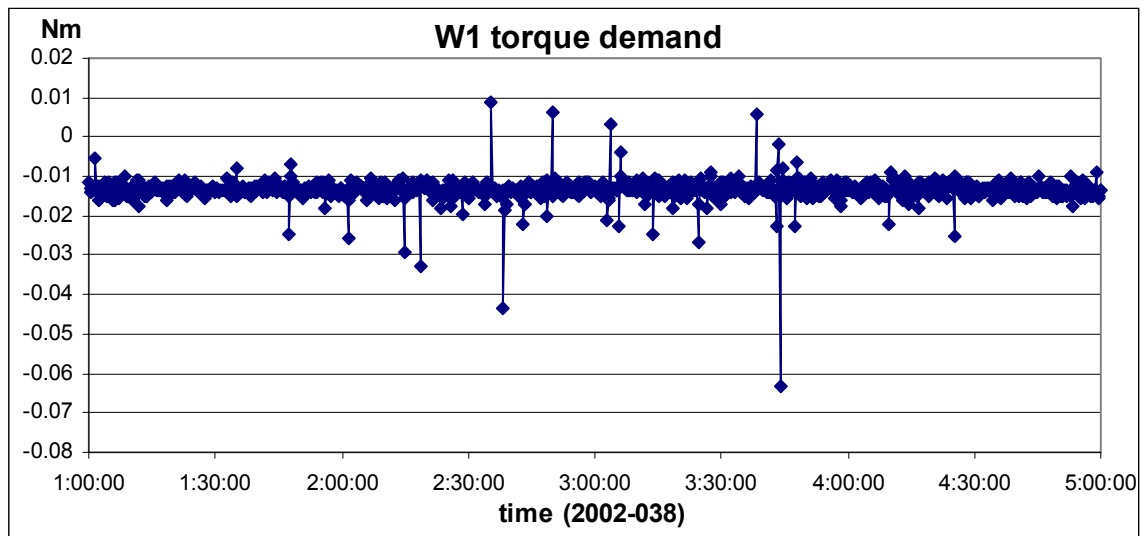
The investigation of numerous torque demand errors in CRP has led us to re-examine the "reaction wheel speed measurement" anomaly. This anomaly, discovered in September 1999, when it had caused a spurious triggering of the new gyroless Hx protection, was not fully understood at that time. With this new analysis, we now have a complete explanation for this anomaly as well as a better understanding of its occurrence and consequences.

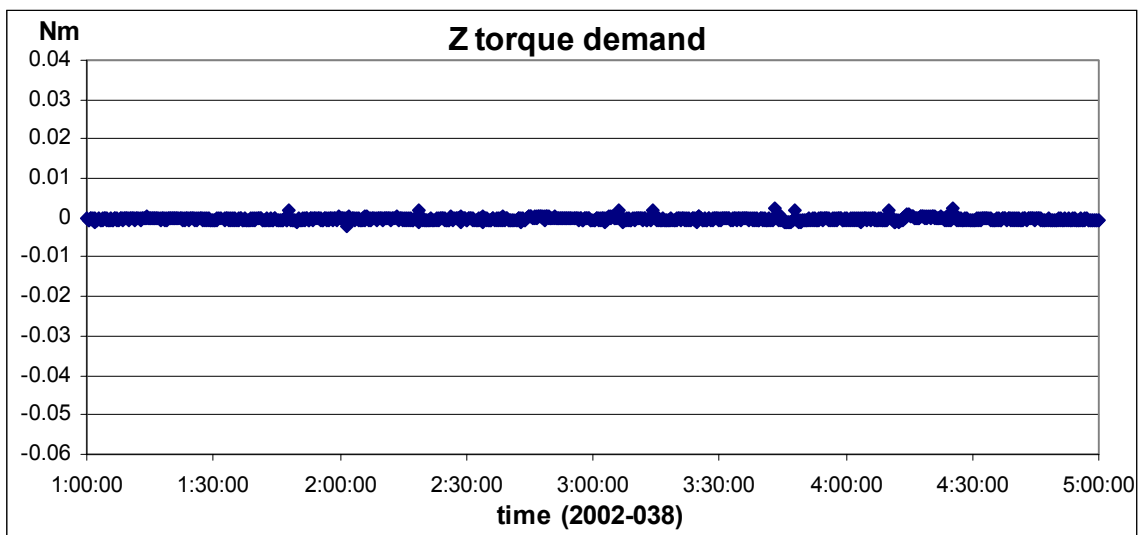
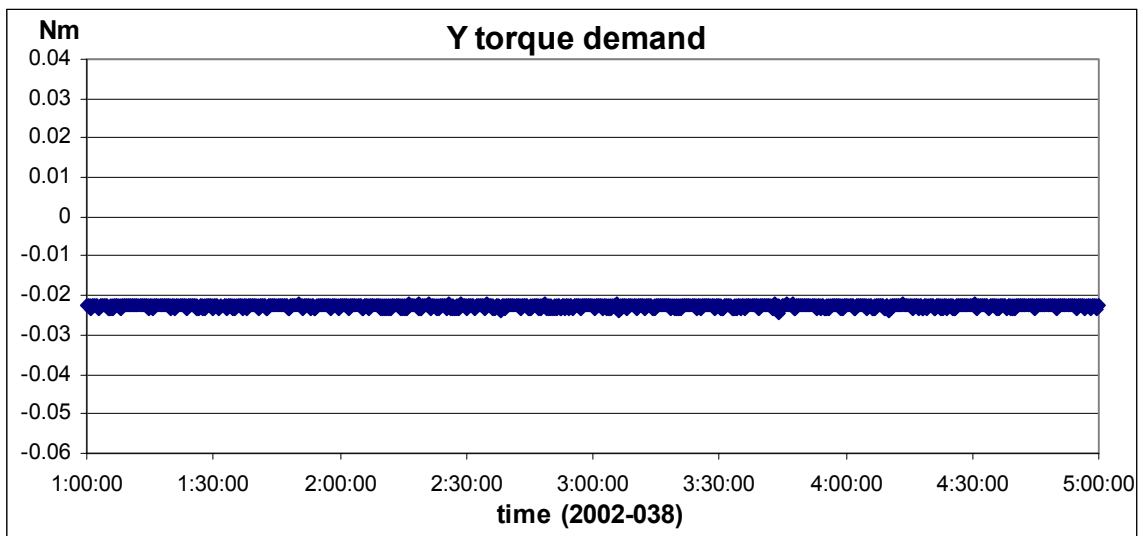
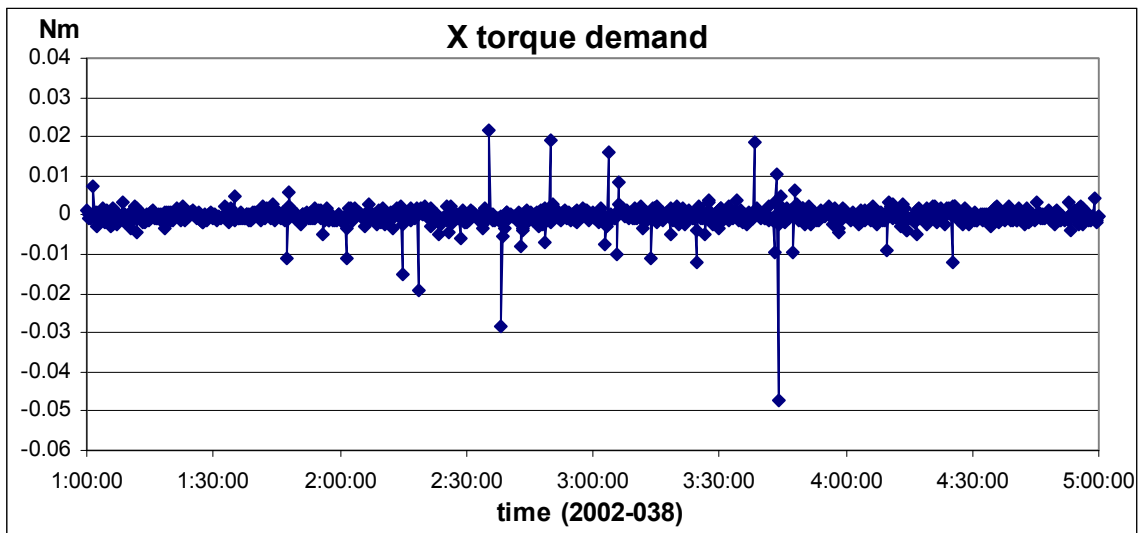
2 Torque demand errors

On 2002-Feb-07 (doy 038), while in CRP as part of the recovery from ESR# 18 (Bus Voltage drop incident), a total of 373 wheel torque demand errors were reported by the ACU software, between 01:46 and 04:24 UT (spacecraft anomaly S02-0017). These errors occurred in 15 bursts of 20 or 40 contiguous errors. One of the bursts had 13 errors only.

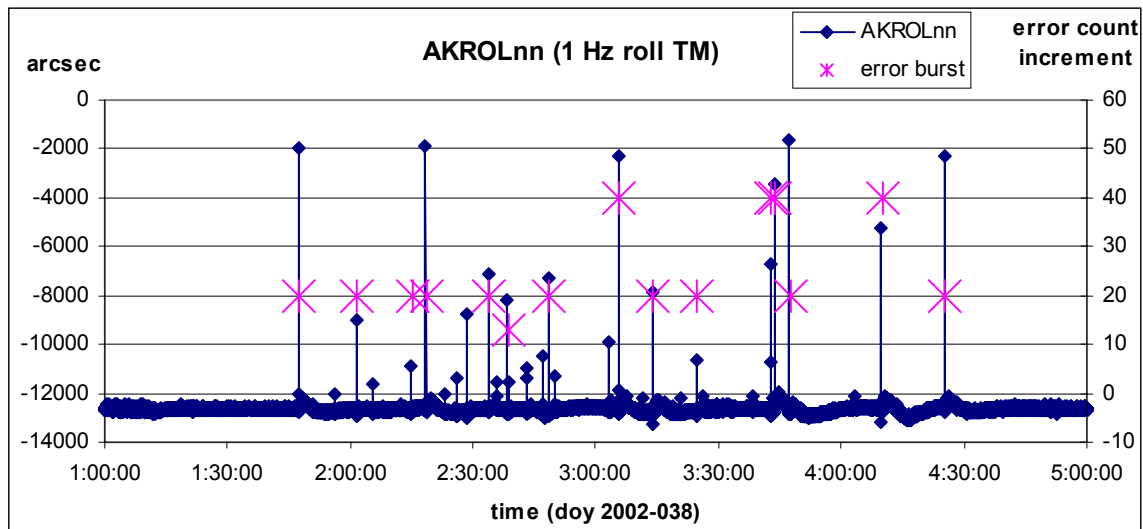


Analysis of the telemetry showed that the unusual torque demands had identical profiles on wheels 1 and 3, ruling out any mechanical problem on a wheel. The conversion of the three wheel torque demands to spacecraft frame, showed that the problem was actually **abnormal roll torque demands**, while pitch and yaw torques were normal.





The abnormal roll torque demands pointed to a problem with the CRS angle measurement, which serves as input to the CRP roll controller. Indeed, the 1 Hz roll telemetry (AKROL00-14) displayed many important glitches, with roll errors in the order of 3°. The larger roll telemetry glitches coincide with the error bursts.



The CRS angle derives from the wheel speeds, so the wheel speed measurements were obvious suspects, all the more that they are affected by a known anomaly.

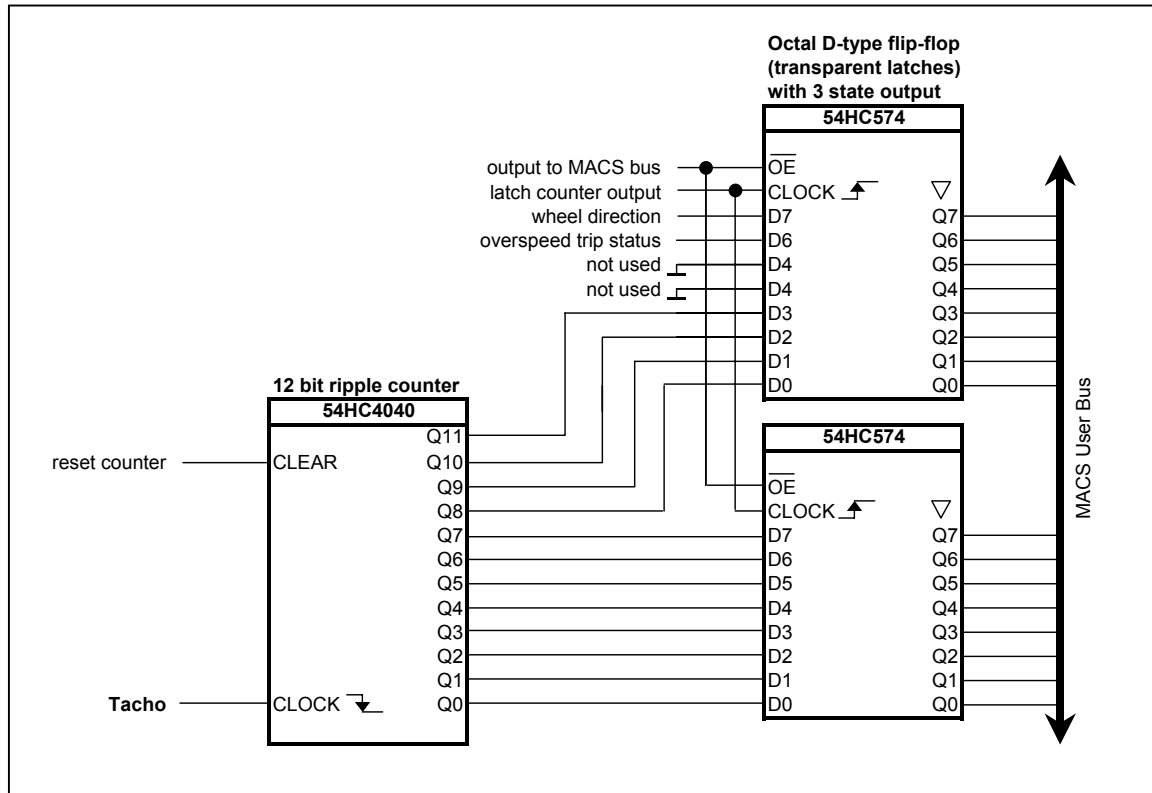
3 Principle of the wheel speed measurement

The reaction wheels generate 240 tacho pulses per revolution. These tacho pulses are counted by an HC4040 12-bit ripple counter. Every 46.875ms, the counter outputs are latched in 2 HC574 8-bit transparent latches, along with the wheel spin direction and the over-speed trip status, then the counter is reset.

The 46.875 timing window is synchronized on the MACS bus. It is obtained by counting 384 MACS sync pulses. There is 1 sync pulse every 25 MACS clock pulses and the MACS clock frequency is 204.8kHz $\rightarrow 384 * 25 / 204800\text{Hz} = 0.046875\text{s}$.

The raw wheel speed is directly the number of tacho pulses counted within the 46.875ms window. This results in an lsb of $60 / (240 * 0.046875) = 5.3333... \text{rpm}$

Wheel tacho counter circuit diagram



4 History of the wheel speed anomaly

The wheel speed anomaly was discovered during the flight commissioning of the gyroless software, in September 1999, with the spurious triggering of the new Hx monitoring function (anomaly S99-0087). By chance, the Corrective Action for this monitoring, which is to trigger ESR, was disabled at that time. The investigation of this incident (see MRB ref. SH-MAT-HO-37945, 1999-11-25) concluded that it was due to a faulty wheel speed acquisition. At the time of the anomaly, wheel 1 speed was 2730.66 rpm, a raw value of 512 in decimal = "0010 0000 0000" in binary. It was postulated that the Hx protection triggered due to the corruption of the single "1" bit into a "0" which resulted in a faulty reading of zero rpm.

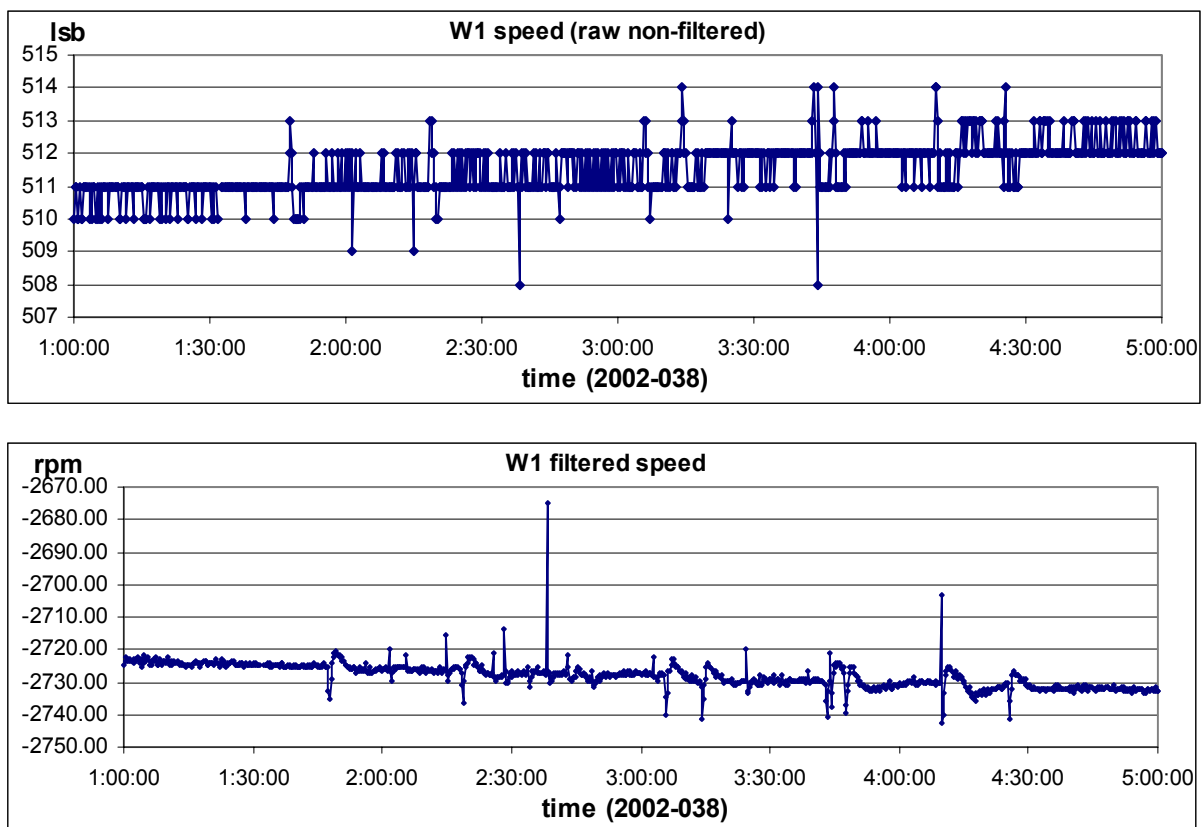
Specific examination of flight telemetry, from various epochs in the mission, showed that the problem had always been present, even just after launch. It remained unnoticed until the gyroless software upload because the wheel speeds, which were previously acquired only for telemetry downlink, were now used on board for control and monitoring purposes.

In every case observed in the flight telemetry, the difference between the correct and the faulty measurements, in raw values, is always a power of 2, or a power of 2 minus 1. Thus, it was concluded that the anomaly was characterized by an occasional corruption of a *single* bit from "1" to "0". Because the faulty measurements are always lower than the correct ones, it was also concluded that corruptions are always from "1" to "0" and never from "0" to "1".

Since September 1999, this anomaly has been followed-up in trending, with the objective of keeping statistics on which bits are corrupted with which frequency. Again, since the focus was on determining which *single* bit was corrupted, only the deltas between correct and faulty measurements were analyzed, without observing the faulty binary patterns themselves.

5 New analysis

During the torque-demand-error episode, on 2002-Feb-07, the large number of the wheel speed telemetry corruptions, observed in such a short time, did not fit with the prevailing theory of occasional single "1" to "0" bit flips.



It is interesting to note that the corruptions occurred only when the speed was between 511 and 512 raw counts. There are no corruptions between 510 and 511, and, most remarkably, there are no corruptions between 512 and 513. Thus, the anomaly is not directly related to the "infamous" 512 (0010 0000 0000 bin) value, for which a single bit-change can give a faulty 0 rpm reading. This showed that our previous understanding of this anomaly was incorrect.

A new analysis of the wheel speed glitches in the trending data, with special attention to the faulty binary patterns, instead of just deltas, immediately revealed that many faulty readings could not be explained with a single bit change. For example, on 1999/323/15:04:24, while wheel 2 was between 2384.00 rpm and 2389.33 rpm, a faulty value of 2304.00 rpm was acquired. The following table shows the associated raw binary patterns:

year	doy	time	date	wheel	sample	RPM	raw dec	binary	break-down	bits to chg.
1999	323	15:04:24	1999-11-19	2	OK (odd)	2384.00	447	0110111111	011011-1111	4
					NOK	2304.00	432	0110110000	011011-0000	
					OK (even)	2389.33	448	0111000000	011100-0000	3

The faulty 432 sample cannot be explained by a single bit change:

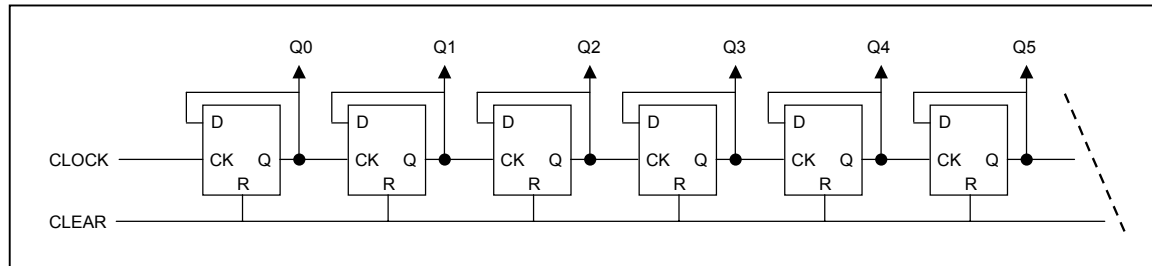
- From 447 (raw dec), 4 bits must be changed.
- From 448, 3 bits must be changed (2 of them from 0 to 1).

Another interesting example:

year	doy	time	date	wheel	sample	RPM	raw dec	bin	break-down	bits to chg.
2000	192	04:09:28	2000-07-10	1	OK (odd)	2725.33	511	0111111111	0111111-111	3
					NOK	2688.00	504	0111111000	0111111-000	
					OK (even)	2730.67	512	1000000000	1000000-000	7

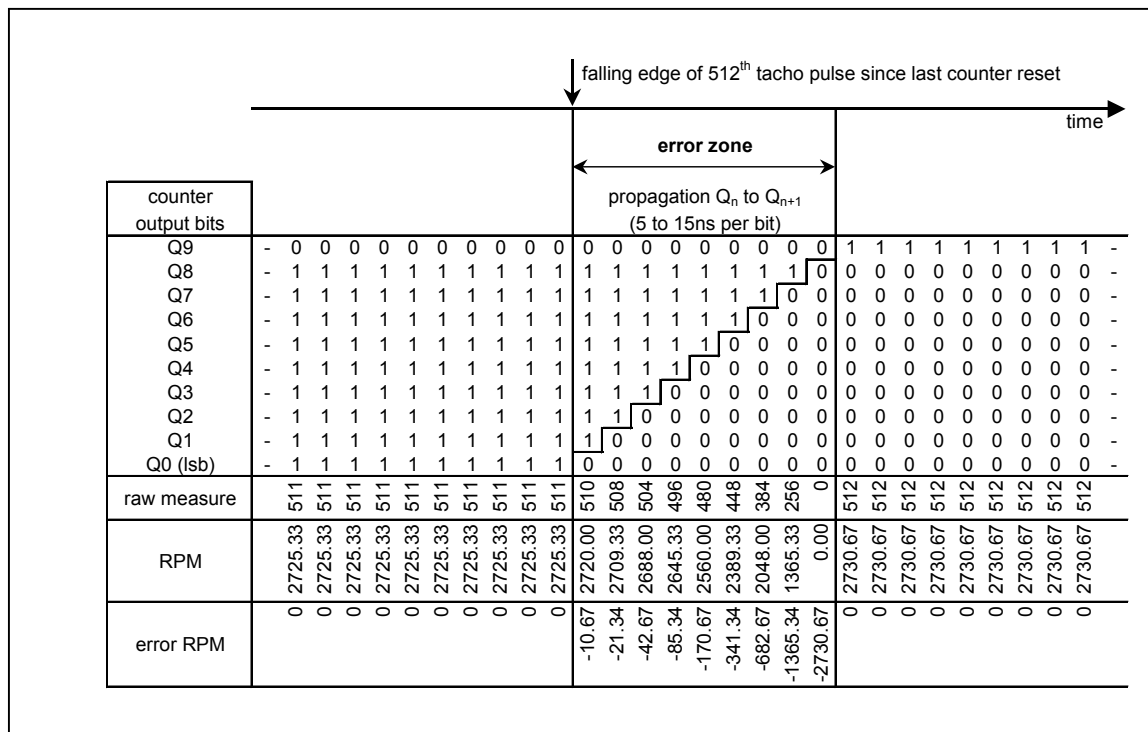
Looking at the break-down of the faulty binary patterns, the true nature and the origin of the anomaly becomes obvious: the counter output is latched while carries have not finished propagating through the counter stages. Indeed, the HC4040 is a *ripple* counter. Unlike a synchronous counter (ex: HC193), the outputs do not change synchronously with the clock, the counting propagates through the 12 stages of the counter, with a certain delay, from one stage to the next.

HC4040 counter logic diagram



The HC4040 datasheet specifies that the propagation delay, from one counter stage to the next (Q_n to Q_{n+1}), is between 5 and 15ns, depending on supply voltage and temperature. Consequently, if the current count ends with consecutive “1” bits, the next increment will result in the propagation of a carry through several stages of the counter. Until the propagation is over, the counter outputs are incorrect. The following figure illustrates this.

Counter timing diagram

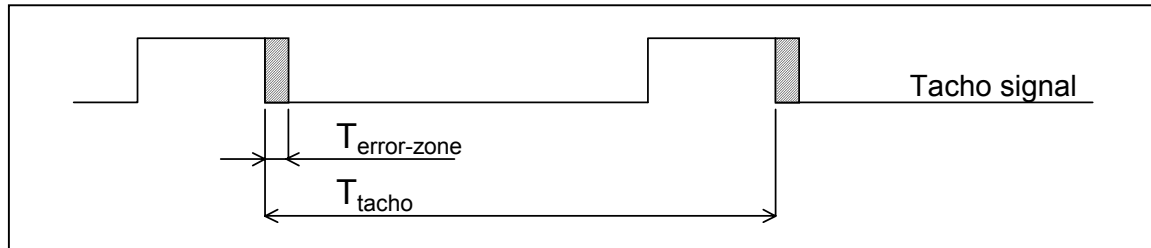


If the end of the 46.875ms timing window occurs in the carry-propagation "error zone", then a wrong measurement is latched.

6 Implications

6.1 Probability of errors

This anomaly is not purely probabilistic. In theory, an error can occur at every acquisition if the wheel speed and the 46.875ms window phasing are, and remain, just right. In practice, however, this is quasi impossible and it seems reasonable to consider that the tacho pulses and the 46.875ms timing window are not correlated. The probability of an error is then the ratio of the propagation error zone to the tacho period.



probability of error : $P_{\text{error}} = \frac{T_{\text{error-zone}}}{T_{\text{tacho}}}$ with $T_{\text{tacho}} = \frac{60}{240 * \text{RPM}}$

The following table lists the wheel speeds having a potential for at least 6-bit (-336 rpm) errors. The table also shows the probability of the largest possible error at that speed, assuming a 10ns/bit propagation delay, as well as the average period (in minutes) of such an error for the actual 20Hz sampling rate. The same is given for all errors of 6 or more bits.

True wheel speed			Largest possible error at that speed				6 (or more) bit errors	
rpm	raw dec	raw bin	bits	rpm	probability	period (mn)	probability	period (mn)
336.00	63	0000111111	6	-336.00	1.34E-05	62	1.34E-05	62
677.33	127	0001111111	7	-677.33	2.71E-05	31	5.42E-05	15
1018.67	191	0010111111	6	-336.00	4.07E-05	20	4.07E-05	20
1360.00	255	0011111111	8	-1360.00	5.44E-05	15	1.63E-04	5
1701.33	319	0100111111	6	-336.00	6.81E-05	12	6.81E-05	12
2042.67	383	0101111111	7	-677.33	8.17E-05	10	1.63E-04	5
2384.00	447	0110111111	6	-336.00	9.54E-05	9	9.54E-05	9
2725.33	511	0111111111	9	-2725.33	1.09E-04	8	4.36E-04	2
3066.67	575	1000111111	6	-336.00	1.23E-04	7	1.23E-04	7
3408.00	639	1001111111	7	-677.33	1.36E-04	6	2.73E-04	3
3749.33	703	1010111111	6	-336.00	1.50E-04	6	1.50E-04	6
4090.67	767	1011111111	8	-1360.00	1.64E-04	5	4.91E-04	2

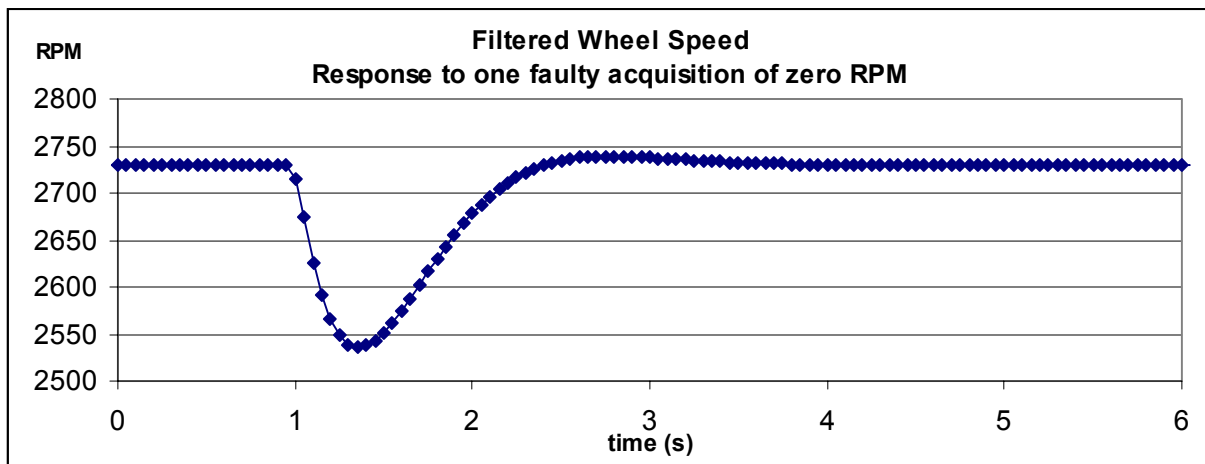
On 2002-Feb-07, the average period of the torque demand error bursts, was 11 minutes. Theoretically, a 7ns propagation delay would result in such a period for 9-bit errors at 2725.33 rpm.

6.2 Consequences

The wheel speeds are used on board for the following:

- wheel speed control loop, in SBM (standby mode). Due to the low saturation torque (only 0.05Nm) and the high bandwidth of this control loop, a faulty reading will not have a significant effect on the actual wheel speed.
- wheel speed monitoring, in NM and RMW. The COBS filter value of 3 formats makes this protection relatively immune to faulty wheel speed readings. However, there is no absolute guaranty. Anyhow, the corrective action (transition to CRP) is not dramatic.
- Hx monitoring in CRP, RMW and NM. Note that the spurious triggering of this protection, in September 1999, led to the discovery of the wheel speed anomaly. Since then, the Corrective Action (ESR) was left disabled.
- CRS angle in CRP, used for roll control and High Gain Antenna pointing (SK table).

In CRP, the roll attitude is given by the CRS angle, which is derived from the filtered wheel speeds.



During the torque-demand-error episode on 2002-Feb-07, the 1Hz roll telemetry showed errors in the order of 3° . These erroneous inputs have disturbed the roll control and resulted in actual roll offpointings in the order of 0.1° .

A worst case analysis shows that the error on the CRS angle, due to a single faulty acquisition, can reach 54° , with wheel speeds of 2730/ 190/ 2633 rpm for example. This would result in an actual roll offpointing in the order of 1.8° . In theory, a 180° roll telemetry error is possible during a roll profile with wheel speeds of 2730/ 0/ 2550 rpm for instance.

A large roll telemetry error can also result in a large movement of the High Gain Antenna, through the SK table, possibly leading to the loss of medium or high rate telemetry and the triggering of the HGA monitoring.

It should also be noted that small errors of 2 or 3 bits are common: $1/4^{\text{th}}$ of all wheel speeds have a potential for 2-bit errors, $1/8^{\text{th}}$ have a potential for 3-bit errors. Although these small errors have small effects, they could be a significant contributor to the roll attitude noise in CRP.

7 Conclusion

We now have a complete understanding of the wheel speed measurement anomaly and its consequences.

This anomaly is inherent to the hardware design of the tachometer.

The most serious potential consequences are:

- roll attitude noise and transients in CRP, up to several degrees offpointing.
- large High Gain Antenna offpointings, leading to the loss of telemetry and the triggering of the HGA monitoring.

However, it could be possible to design a simple ACU software patch in order to filter-out the erroneous wheel speed measurements and avoid the adverse effects of this anomaly.

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